Accuracy of dimension measurements from neutron radiographs of nuclear fuel pins

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Publication date:
1976

Document Version
Publisher's PDF, also known as Version of record

A. E. K. Risø

Risø - M - 1860

Risø - M - 1860

Title and author(s)

Accuracy of dimension measurements from neutron radiographs of nuclear fuel pins

by

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Date 26.03.76

Department or group

Metallurgy

Group's own registration number(s)

A-193

8 pages + 2 tables + 4 illustrations

Abstract

Paper to be presented on 8.9.76 to the Eight World Conference on Nondestructive Testing in Cannes, France.

A review is given of different methods used for dimension measurements from neutron radiographs and results are presented of an investigation performed, using unirradiated fuel pins with calibrated UO_2 pellet diameters and fuel-to-clad gaps.

Projection microscope, three types of travelling microdensitometers and an electronic image analyzer were used to measure diameters and gaps from neutron radiographs produced at Risø DR1 and Studsvik (Sweden) R2 reactors, using different brands of X-ray films and transfer technique with 0.1 mm Dy foil.

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FI 25-20-

ISBN 87-550-0392-3

EIGHTH WORLD CONFERENCE ON NONDESTRUCTIVE TESTING
HUITIEME CONFERENCE MONDIALE SUR LES ESSAIS NON DESTRUCTIFS

Title / Titre: ACCURACY OF DIMENSION MEASUREMENTS FROM NEUTRON RADIOGRAPHS OF NUCLEAR FUEL PINS
PRECISION DES MESURES DE DIMENSIONS SUR LES NEUTRONOGRAMMES DES CRAYONS DE COMBUSTIBLE NUCLEAIRE

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SUMMARY: Comparison of accuracies obtained with measuring the dimensions (pellet diameter and fuel-clad gap) from neutron and X-ray radiographs of a calibrated nuclear fuel pin performed with a projection microscope, microdensitometers and a video micrometer.

RESUME: Comparison des précisions des mesures (diamétre de pastille et jeu radial pastille-gaine) sur les radiogrammes neutroniques et roentgenographiques d'un crayon de combustible nucleaire étalonné, effectuées par un projecteur de profil, des microdensitometres et un video micrometre.

I. INTRODUCTION

In order to judge the behaviour of nuclear fuel pins after irradiation in a reactor, it is essential to quantitatively assess the dimensional changes occuring in the fuel itself (UO_2 pellets) and the cladding (zircaloy tube), and to compare these with preirradiation measurements. Neutron radiography contains adequate information about such phenomena as swelling or cracking of the cladding or cracking of the fuel, which can occur during irradiation. To extract this information from neutron radiographs, one must have an accurate method oq measuring dimensions on the X-ray films on which neutron radiographs are taken.

Although it is comparatively easy to see even minute changes of dimensions on the neutron radiographs, it is very difficult to measure them accurately, The problem is to measure density differences on X-ray films giving a rather unsharp contour of the object radiographed. Neutron radiograms can be produced either on X-ray films (double or single coated), on plastic films (track-etch technique) or even on X-ray paper. The present investigation was limited to X-ray films only.

II. METHODS OF DIMENSION MEASURING

The following methods have been reported for dimension measurements of nuclear fuel from radiographs:

II.1. Travelling microscope and light-table micrometer

The possibility of using a low power travelling microscope was examined at Harwell [1]. This method of measuring a neutron radiographic image was clearly unsatisfactory and hence it was abandoned. The diameters and length of a specimen was measured from a neutron radiographic image a Batelle-Columbus [2] on a light table using specially constructed micrometer. Quite good accuracy was obtained (measurements agreed within a few per cent with subsequent micrometer measurements).

II.2. Optical projector

A low magnification (10 x) optical projector was used by several investigators [3], [4], [5]. The dimensions determined by this method proved to be smaller than the actual ones. A 20 x projector was used a Grenoble [6]. The accuracy of this method was comparable with that of a travelling microdensitometer.

II.3. Travelling microdensitometer

The instrument most widely used for the measurement of dimensions from neutron radiographs is the travelling microdensitometer. Several of the investigators have used the Joyce Loebl Mark III C, MK III CS, or MK 3 CS models. Such a microdensitometer was used during the work performed at Harwell [3], [4], and probably in [1]. Reference is also made to it in [6]. The authors of [2], [5] and [7] do not specify the type of microdensitometer they used, whereas measurements at Studsvik [8] were performed on a home-built densitometer.

The problem of determining the specimen diameter from densitometer trace has been investigated by many authors. In [7] two methods are compared: one in which the diameter is determined from the distance between points of intersection between specimen density trace and base density, and the second in which the diameter is deter determined from the distance along abscissa for $T_{1/7}$ values. The second method was proved to be more accurate [7].

The authors of [1] came to the conclusion that the 1/8 mean height is the best position for diameter determination. The dimensions determined by microdensitometer scans were larger than the actual dimensions. In [6] gaps between fuel and cladding were measured as distances between maximum and minimum densities on microdensitometric traces. An agreement with physical measurements within ± 50 µm was reached for gaps ranging from 610 to 1780 µm. [2] states in general that postirradiation neutron radiographs and micrometer measurements agree within a few per cent. The measurements performed at Studsvik [8] with a specially built scanning microdensitometer showed reproducibility of densitometric recordings of unirradiated pellets of ± 10 µm. The authors state that the conventional transfer technique will not permit evaluation and direct measurement of radial gaps of less than 100 µm.

II.4. Photographic enlargement and sharpening

Photographic enlargement (10 x) and sharpness improvement by copying of radiographs showed lack of sharpness, and this method was judged unsuitable for direct measurements [1].

II.5. Photographic image enhancement

To determine how closely dimensions read from neutron radiographs can agree with mechanical measurements, diameters of cylindrical oxide fuel specimens were measured from neutron and X-ray radiographs in [9]. Photographic enhancement was applied. This consisted of a special film reproduction technique to separate and record isodensity contours. X-radiographs gave greater diameter values than mechanical measurements, which in turn were greater than those obtained from enhanced neutron radiographs. The neutron radiographic measurements were within a band of ± 30 µm of the mechanical measurements.

II.6. Electronic image analyzer

The application of electronic image enhancement technique to radiography seems to be very promising (though costly). Work performed in that field by Carr [10] on experimental fuel-to-clad gaps consists of a comparison between microdensitometer, video and micrometric measurements. With a 30 x magnification of the video system, its diameter readings generally fell between those obtained with the microdensitometer and direct micrometer gaging. Further work on video measurements [11] confirmed those results.

III. TEST SPECIMENS

Throughout the present investigation two test specimens were used: special fuel pins containing UO_2 pellets from natural and enriched uranium clad in zircaloy tube and a 0.1 mm dysprosium plate with slits. Two special fuel pins were produced (fig. 1) in which 7 UO_2 pellets were enclosed in a zircaloy tube (OD = 14.3, ID=12.65, WT = 0.825 mm). One of the pellets had a diameter of 12.04 mm, whereas the remaining

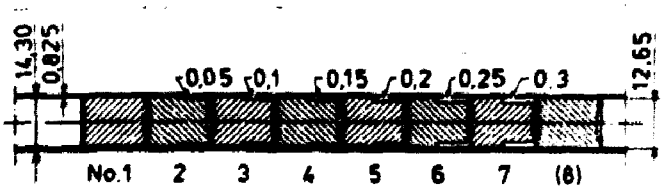

Fig. 1. Fuel pin with UO_2 pellets and calibrated fuel-to-clad gaps.

six pellets had this same diameter on half of its height. The other half of these six pellets was ground down to such a diameter that a gap was formed between pellet and cladding. The radial gaps were 50,100,150,200,250 and 300 μm wide. To judge the accuracy of different measuring methods, used for diameter and gap determination, a 0.1 mm thick dysprosium foil was used, in which two parallel slits were cut (by electro-erosion). The slits were 200 μm wide and were 12 mm apart.

IV. IMAGING TECHNIQUE

The calibration fuel pins were radiographed with X-rays and neutrons (beam axis perpendicular to pin axis). The thickness of the zircaloy in the cladding and the thickness of the UO_2 pellet penetrated during radiography are shown on fig. 2 as a function of pin radius (for different gaps). Radiation of an intensity J_0 will be attenuated according to the attenuation law: $J = J_0 e^{-\mu t}$, where μ is the linear attenuation coefficient for zircaloy, UO_2 or a combination of both. The radiation of intensity J, emerging from the pin, will next strike either the imaging foil (neutronography) or the X-ray film directly (X-radiography). On neutron or X-ray radiograms the film density will be produced as shown schematically on fig. 3. While going over from the radiation intensity curve to the density distribution curve it must be remembered that the contrast of X-ray film increases with density, so that the lowest curve in fig. 3 will be steeper un its upper region (high radiation intensity, high film contrast) and flattened out in the lower region (low radiation intensity, low film contrast).

Neutron radiographs were taken both at the DR 1 reactor, at the DAEC, Risø, as well as at the R 2 reactor, AB Atomenergi, Studsvik, Sweden. At the DR 1 the thermal neutron flux was 10^7 n/cm^2·s at the edge of the concrete shielding. The beam port was 10 x 10 cm [12]. The R 2 reactor had a thermal neutron flux of 2 x 10^7 n/cm^2·s at the object plane [8]. In both reactors neutron radiography was performed by the transfer method using 0.1 mm dysprosium foils. At Risø, several X-ray film brands were used (Kodak and Agfa-Gevaert) and at Studsvik single coated Kodak R and Agfa-Gevaert D 4 films. Characteristic curves of several brands of X-ray films were made in such a way that the calibration fuel pin was placed before the Dy foil and exposed for different times in the neutron beam. Whereafter the foil was immediately put into contact with the film, which was exposed overnight. X-ray film densities were measured under the middle of the pin and were used to compute the characteristic curves. The calibration fuel pins were also radiographed at Risø with an Andrex 300 kV machine (focal spot 3 mm) at 140 and 220 kV on different X-ray film brands.

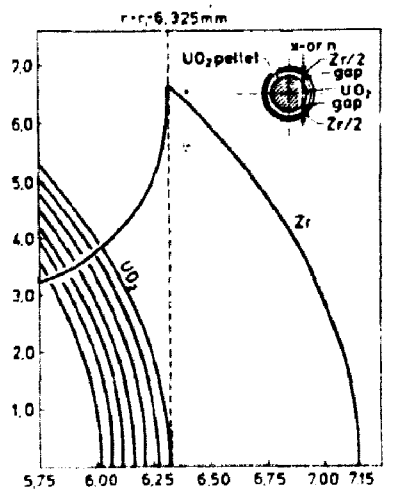

Fig. 2. Thickness of zircaloy tube and UO_2 pellets penetrated by X-rays or neutrons.

Pictures of the Dy foil were produced on X-ray films using visible light, X-rays and neutrons. The distance between the two slits and slits widths were directly measured on the projection microscope and on a traveling microdensitometer.

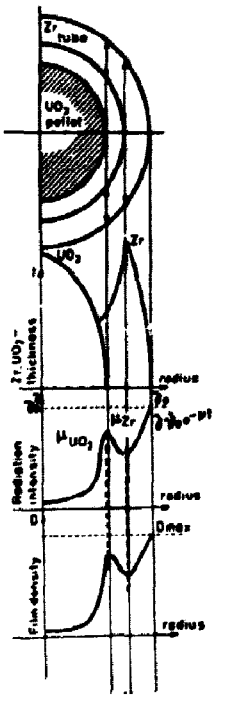

Fig. 3. Radiation intensity and film density.

V. MEASURING TECHNIQUE

The diameters and gaps of the calibration fuel pins, as well as the distance between slits and slits widths of the Dy foil were measured on neutron and X-ray radiographs using the following measuring instruments:

V. 1. Projection microscope

A Nikon profile projector, model 6 C was used that permits magnifications of 10,20,50 and 100 x. Only the readings performed with 10 x magnification gave reliable results. Higher magnifications could not be used because the relatively high densities of the radiographs rendered the microscope picture illegible. A newer type of Nikon projector, model 6 CTR-2, was also tested. This gave better results, but also in this case higher magnifications proved impracticable.

V. 2. Travelling microdensitometers

Three types of travelling microdensitometers were used throughout the investigation. (1) A Baird double-beam densitometer and comparator, available at Risø, could be used for scanning radiographs with densities below 2. It could be operated at two fixed scanning speeds, 5 and 25 µm/s. The output of the microdensitometer was fed to a paper strip chart recorder with different paper speeds and measuring sensitivities. By choosing a suitable combination of scanning and paper speed and recorder sensitivity, densitometric scans of good quality could be produced, from which the dimensions of interest could be computed. The use of the Baird microdensitometer embodied two disadvantages: high density radiographs could not be measured and the use of two scanning speeds only was impractical (the slow speed desirable for gap measurement gave excessively long measuring times while the high speed, desirable for diameter measurements did not reproduce the gaps accurately enough. A linear magnification of 30 x was chosen for the assessment of test specimens.

(2) A Joyce Loebl microdensitometer was not available at Risø. Nevertheless, some test measurements were performed at the Joyce Loebl factory at Gateshead (England) using the newest MK 3 CS model. There a slit of 40 x 1000 µm with a magnification of 200 x gave good results when measuring pellet-to-clad gaps. However, when measuring both the diameter and the gap from one single scan, such high magnification could not be used (microdensitometric scans are recorded on A4 paper). Therefore, for the objects under investigation (outside diameter of the calibration pin 14.3 mm) maximum magnification of 10 x could be used. This presented some difficulties in reading gaps (a 50µm gap was reproduced as two peaks separated by 0.5 mm distance on the recorded scan).

A series of measurements was also performed using an older type Joyce Loebl MK III C model at Århus University. A magnification of 10 x was used for these measurements.

(3) The best advantages in the use of assessing neutronographs were presented by the travelling microdensitometer constructed by I. Gustafsson at Studsvik. This instrument has not only the advantage of controlling the scanning slit width and length, but also of being able to change the scanning speed continuously, while retaining full control of the scale factor in travelling speed. This is made possible by application of two step motors (driving the scanning table and the paper of the recorder), both supplied by the same variable frequency oscillator. In addition a special pen marks on the recorder paper the distance travelled by the microdensitometer slit at 10 mm increments.

By using the Studsvik microdensitometer it was possible to rapidly and accurately scan radiograms of calibration fuel pins (the gaps with low speed and the rest of the radiograph with high speed). Best results were obtained using a 50 x 400 µm slit.

(4) The calibration pin was not only radiographed by neutrons but also by X-rays. For an unirradiated pin X-rays give the best results, and this can be used as reference when assessing the accuracy of the neutron radiographs. To give an idea of the performance of the three microdensitometers described above traces of X-ray and neutronographs of the calibration fuel pin are reproduced on fig. 4.

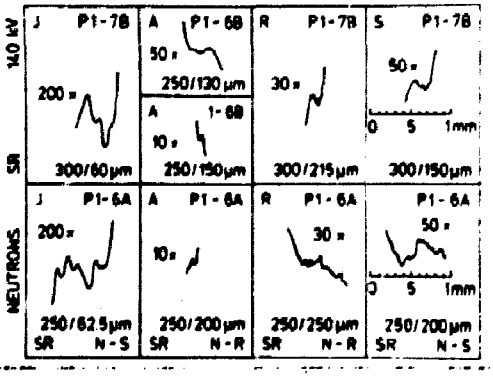

Fig. 4. Traces of X-ray and neutron radiographs of the calibration fuel-to-clad gaps.

V. 3. Electronic image analyzer

A spatial Data System electronic image analyzer equipment, available at the HDT Centre at Harwell was used to make a number of measurements on selected radiograms. The SDS Edge Enhancer 401 with Video Micrometer 420, Density Profile Display 703-3 and Digital Density Readout 704-4 were used for this purpose.

VI. MEASURING RESULTS

Table 1 summarizes the scope of the investigation.

Table 1. Scope of the investigation

Radiation			X-rays								Neutrons																Visible light			
			140 kV						230 kV		DR2-Risø							R2-Studsvik												
Sample / Film / Measuring apparatus			PM	TMD				LIA	PM	TMD	PM	TMD					LIA	PM	TMD				LIA	PM	TMD			LIA		
			B	A	S	A	J	B	B	S	B	L	B	S	A	B		B	L	S	A	J	B	B	B	A	B			
Agfa - Gevaert	Single coated D 2	Dy	x	x		x																		x	x	x				
	D 2	P1	x	x					x		y		x																	
	D 4	P1	x	x	x	x		x	x	x	x		x	x	x	x		x		x	x		x							
		P2	x	x							x	x		x	x	x		x	x	x	x		x							
		Dy	x	x		x					x				x									x	x	x	x			
	Copy of D 4	P1													x						x									
		P2													x						x									
	D 7	P1	x	x					x		x		x																	
	D 10	P1	x	x					x		x																			
	Scientia 10 E 56	Dy	x	x		x																		x	x	x	x			
Kodak	Single coated R	P1	x	x	x	x	x	x	x		x		x	x	x	x		x		x	x	x	x							
		P2	x	x	x						x	x		x	x	x		x	x	x	x									
		Dy	x	x		x					x		x		x	x								x	x	x	x			
	Copy of s.c.R	P1													x						x									
		P2													x						x		x							
	R	P1	x	x					x		x		x																	
	M	P1	x	x					x		x		x																	
	C	P1	x	x					x		x		x																	

PM - Projection microscope: N-Nikon 6C, L-Nikon 6CTB-2; TMD - Travelling microdensitometer: N-Baird, S-Studsvik A-Joyce Loebl MK IIIC, J-Mk 3 CS; EIA - Electron image analyser: H-Harwell. Calibration fuel pins: P1-with natural U, P2- with enriched U; Dy - calibrated Dy plate

From the above program radiographs made on D 4 (neutronograms made routinely at Risø) and single coated R films (neutronograms made at Studsvik) were chosen for the final comparison of measuring accuracies. Radiographs made with X-rays served as reference for neutron radiographs. The results of dimension measurements are presented as per cent deviation from true diameter or from the gap.

VI. 2. X-rays

Pellet diameters and fuel-to-clad gaps could be easily seen with the naked eye on the radiographs. Several persons have read the dimensions with the projection microscope, giving different results. Whereas it was comparatively easy to read all the diameters, it was rather difficult to read the smallest gap, i.e. 50 µm. Measurements on pellets with gaps larger than 150 µm gave results lying close to the micrometric measurements. Diameter readings deviate less than - 1 % from the true dimensions. The largest diameter deviation was -0.8 % on pellet No 4, which corresponds to ca. -100 µm. Most of the readings gave results smaller than true. Deviations in gap readings were much larger (percentual), going up to 45 % on a 100 µm gap or 20 % on a 300 µm gap. Gap measurements showed larger values for small gaps and smaller values for larger gaps.

Using the projection microscope the accuracy of pellet diameter measurements can be assumed to be 100 µm, and 60 µm for gaps.

Pellet diameter and fuel-to-clad gaps were measured with four different microdensitometers. All diameter measurements showed values larger and all gap measurements values smaller than true. With the microdensitometer used at Risø and at Studsvik the maximum deviation for diameter measurements was smaller than + 4 %, i.e. +460 µm. The measurements performed with the Joyce Loebl instruments showed deviation less than + 2.1 %, i.e. + 260 µm. The deviation in gap measurements with all densitometer models could be as high as - 70 %. For a 300 µm gap this means a deviation of - 210µm.

X-ray radiographs were measured at Harwell by means of the SDS Video Micrometer, Densitometer Profile Display and Digital Density Readout. Pellet diameters were either measured directly from the picture displayed on the monitor using the two refe-

rence marks, controlled by the joysticks of the video micrometer, or from the density profile display on the monitor (by means of the same two reference marks and joysticks). Measurements made directly from the radiographic picture showed better agreement with the true dimensions (deviation around ± 1 %, corresponding to ca. ± 125 µm), whereas those taken at the density profile had a deviation of up to 2 %, i.e. ca. 250 µm. It was almost impossible to measure gaps (at the magnification used), either directly or from the density trace.

X-ray radiographs were used as references for the assessment of measuring accuracy under the assumption that X-rays can give radiographs of much better quality than neutrons. The investigation demonstrated that even with the best exposure technique and all measuring instruments tested it was not possible to measure gaps of the order of 50 µm. Pellet diameter measurements could be performed with highest accuracy (100 µm) when using the projection microscope. Slightly less accurate results were obtained with the electronic image analyzer technique while reading diameters directly from the radiographic picture (125 µm). The accuracy achieved with travelling microdensitometers was about twice as poor (260 µm). Similar results were reached for gap measurements. Here, best accuracy was reached with the projection microscope (60 µm) and far less accuracy with the microdensitometers (210 µm). It was almost impossible to measure gaps with the video technique.

VI. 3. Neutrons

Calibration pins P1 and P2 were radiographed with neutrons both at Risø and at Studsvik. There were no outstanding differences in radiographic quality and therefore results obtained with both neutron sources are compared together.

All diameter measurements with the projection microscope showed values lower than true. The greatest deviation did not exceed -3 %, which for the largest diameter means -380 µm. Gap measurements showed deviations in both directions: from -40 to + 130 %. For gaps larger than 100 µm deviations could be as large as -65 and + 195µm. For the larger gaps (200 µm and above) gap deviations were a little smaller. There were no substantial differences in the accuracies of dimension measurements from the D 4 and single coated R films. Slightly better results were obtained, though, with the 6 CTR-2 projection microscope (brighter light source).

Similar to the X-rays all diameter measurements made on neutron radiographs with the microdensitometer showed values larger than true. They did not exceed + 5 %. The results obtained with the Studsvik microdensitometer were slightly better than those with the Joyce Loebl. The largest deviations in diameter measurements could reach values as high as + 600 µm. For gap measurements deviations were observed in both directions (+ and -). Most of the gap measurements showed values smaller than true (down to about - 90 % or - 270 µm) but some were also larger (by as much as +50% or 100 µm). None of the microdensitometers in use showed remarkably better results.

Comparing results obtained with the two brands of X-ray films a slightly better accuracy for the single coated R film was noted.

Poor accuracies obtained in gap measurements on the Joyce Loebl microdensitometer are due to the fact that a single densitometric trace was made both for the diameter and the gaps. Therefore the gaps could be read with poorer accuracy than the diameter. The possibility of slowing down the scanning speed while measuring the gaps (like the Studsvik densitometer) gives a higher accuracy of gap measurements. This was, however, impossible with the Joyce Loebl densitometers in use.

Similar to the X-rays only diameter measurements were possible with the electron image analyzer. As could be expected accuracies with neutron were worse than on X-ray radiographs. Measurements made directly from the radiographic picture displayed on the monitor could deviate as much as ± 2 % from the true values (about ± 250 µm) whereas those taken from the density profile could be even worse: 3.5 % or 420 µm. Diameters read from the single coated R film showed slight improvement in accuracy compared to the D 4 film.

It was almost impossible to accurately measure gaps smaller than No 4 (sometimes gap No 3 could be well measured). Therefore one may conclude that it is irrelevant to measure gaps (or cracks) smaller than ca. 100 to 150 µm, regardless of which instrument is used. There was also a density limit, beyond which accurate measuring was impossible. For all measuring instruments this limit is about D=2. Sometimes taking a copy of the radiograph on a single coated duplicating film increased the relia-

bility of dimension measurements. This was partly due to the reduction of the average density without loss of contrast (details reported in [13]).

VI. 4. Comparison of measuring results

Table 2 summarizes the measuring results both for X-rays and neutrons. Maximum (per cent and absolute) deviation values are given for the different measuring methods used throughout the investigation (marking of measuring apparatus - see table 1).

Table 2. Comparison of measuring results

Radiation			X-rays					Neutrons			
Measuring apparatus / Deviation from true dia.			PM	TMD		EIA		PM	TMD	EIA	
			RAL	RAS	A	DIR	DENS	RAL	ALL	DIR	DENS
Pellet-diameter	Direction	+	X	X	X	X	X		X	X	X
		-	X			X		X		X	X
	Maximum value	%	-0.8	+4	+2.1	±1	+2	-3	+5	±2	±3.5
		µm	-100	+460	+260	+125	+250	-380	+600	±250	+420
Gap	Direction	+	X			-	-	X	X	-	-
		-	X	X		-	-	X	X	-	-
	Maximum value	%	+45	-70		-	-	-40 +130	-90 +50	-	-
		µm	+60	-210		-	-	-85 +195	-270 +100	-	-
	Reliable results for gaps larger than	No	3	3		-	-	3	4	-	-
		µm	100	100		-	-	100	150	-	-

As can be seen, only measurements performed with the travelling microdensitometer gave consistent results for diameter and gap measurements: diameter measurements always gave values larger than the true values, whereas gaps showed always as smaller than true. This is due to the fact that microdensitometric measurements are recorded on chart paper (objective measurements) whereas both measurements with the projection microscope and with the electronic image analyzer are made subjectively by the person using the instrument.

VII. CONCLUSIONS

The following conclusions follow from the investigation presented above:

(1) It is non possible to measure very accurately dimensions of round-shaped parts of nuclear fuel pins (pellet diameters and fuel-to-clad gaps) even from radiographs made with X-rays. Deviations from the true dimensions can be as large as 100µm for diameter measurements, which in relative values gives an accuracy of better than 1 %. It is almost impossible to measure gaps smaller than 100 µm; even with the best measuring method the deviation from the true gap dimensions can be as large as 50 %.

(2) The accuracy of measurements from neutron radiographs is even poorer than that from X-radiographs. The deviations from the true dimensions were about three times as large as those observed for X-rays.

(3) Only the use of the travelling microdensitometer gives an objective measuring method. Measurements with this instrument give values larger than true for the diameter, and smaller for gaps. For accurate and effective microdensitometric measurements it is essential to have the possibility of changing linear scale (scanning speed) during the measurement and thus of measuring gaps with greater accuracies.

(4) The optical projection microscope gives relatively good measuring accuracies. Here diameter readings are usually smaller than true, and gaps readings-larger. It is essential to have a strong light source in the microscope to obtain good accuracies.

(5) Use of the electron image analyzer is no doubt the most attractive method: it gives rapid results in digital form (further processing is possible) and it is less time-consuming. High accuracies (as quoted in [11] for an idealized object) could not

be confirmed during this investigation (the scope of which was rather limited while using the electron image analyzer).

ACKNOWLEDGEMENT

The author wishes to acknowledge the contribution of Messrs. U. Bergenlid and I. Gustafsson in participating in this investigation regarding neutron radiography with the Studsvik R 2 reactor and following measurements with the microdensitometer constructed by Mr I. Gustafsson. Thanks are also due to Mr D. A. Pullen from the NDT Center at Harwell and the Joyce Loebl company at Gateshead for giving me the opportunity of using their equipment. The cooperation of Mr J.Olsen during neutron radiography at Risø and of Mrs S. Pedrinha in performing some of the measurements is also gratefully acknowledged.

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